13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2

A STUDY ON ENERGY DISSIPATING BEHAVIORS AND RESPONSE PREDICTION OF RC STRUCTURES WITH VISCOUS DAMPERS SUBJECTED TO EARTHQUAKES

Norio HORI[1], Yoko INOUE[2] and Norio INOUE[3]

SUMMARY

In the concept of performance based earthquake resistant design, appropriate evaluation of seismic demand and capacity of structures is important, and simple procedures for response prediction are required. In this study, energy dissipating behaviors of reinforced concrete structures with viscous dampers subjected to earthquakes, are investigated, and based on these results, a procedure to predict inelastic response displacement by equalizing dissipated damping and hysteretic energy of structures to earthquake input energy is proposed.
Seismic resisting capacity of viscous damper that is effective device to control earthquake response of buildings passively, is evaluated by damping force and dissipated damping energy, and then appropriate estimation of response velocity is required. In the first part of this paper, properties of response velocity of SDOF (single degree of freedom) system with viscous damper subjected to earthquakes, is investigated. And the concept and examples of a procedure to predict the inelastic response displacement of structures are shown.

INTRODUCTION

Viscous damper is effective device to control earthquake response of buildings passively. But because of phase differences between restoring force of structures and damping force of viscous dampers, that is time lag between maximum restoring force and maximum damping force, it is difficult to design on the basis of resisting force of buildings against inertia force of earthquakes. In the concept of performance based earthquake resistant design, appropriate evaluation of seismic demand and capacity of structures is important, and simple procedures for response prediction are required. In this study, energy dissipating behaviors of reinforced concrete structures with viscous dampers subjected to earthquakes, are investigated, and based on these results, a procedure to predict the inelastic response displacement by equalizing dissipated damping and hysteretic energy of structures to earthquake input energy is proposed.

[1] Research Associate, Graduate School of Engineering, Tohoku University, Sendai, Japan
[2] Graduate Student, Graduate School of Engineering, Tohoku University, Sendai, Japan
[3] Professor, Graduate School of Engineering, Tohoku University, Sendai, Japan

Figure 1 shows time history model of energy response, where E_V is energy by movement, E_H is dissipated hysteretic energy, E_D is dissipated damping energy, $E_D + E_H$ is dissipated energy by structure, $E_D + E_H + E_V = E_I$ is input energy by earthquake. Authors [1] investigated momentary input energy ΔE to indicate the intensity of energy input to structures, and to predict inelastic response displacement of structures by corresponding earthquake input energy to structural dissipated energy. ΔE is defined by increment of dissipated energy ($E_D + E_H$) during Δt that is interval time of E_V =0 (relative movement of structure is zero) as shown in Figure 1. And Δt is period of a half cycle response from one local maximum to next local maximum of response displacement as shown in Figure 2. By considering energy response during a half cycle response, seismic resisting capacity of viscous damper is evaluated by dissipated damping energy not only by damping force.

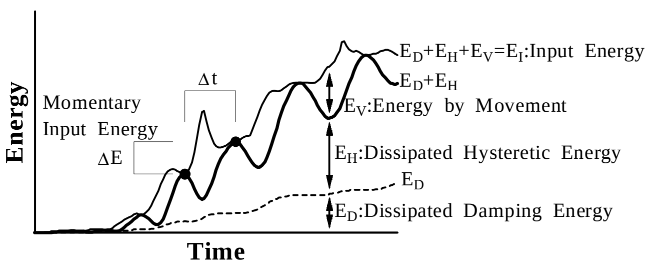


Figure 1. Model of Energy Response

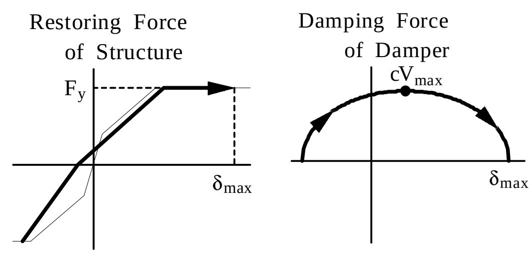


Figure 2. Model of a Half Cycle Response

For estimation of seismic response and resistance of structures with viscous dampers, evaluation of maximum damping force $cV_{\max}$ (c: damping coefficient of viscous damper, $V_{\max}$: maximum response velocity) and dissipated damping energy that depends on maximum damping force, are important. In the first part of this paper, properties of response velocity of SDOF (single degree of freedom) system with viscous damper subjected to earthquakes, is investigated. And the concept and examples of a procedure to predict inelastic response displacement of structures are shown.

ANALYTICAL METHOD

Elastic SDOF system with viscous damper is used to investigate behaviors of response velocity. Damping factor of this system is h =0.10.

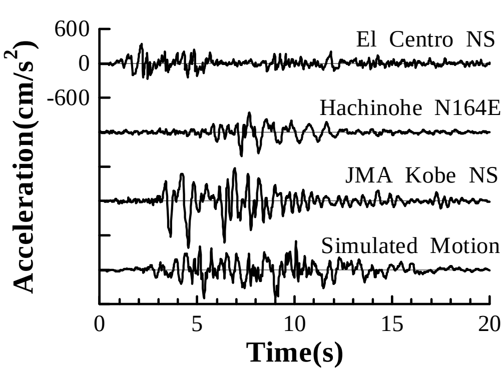


Figure 3. Input Ground Motions

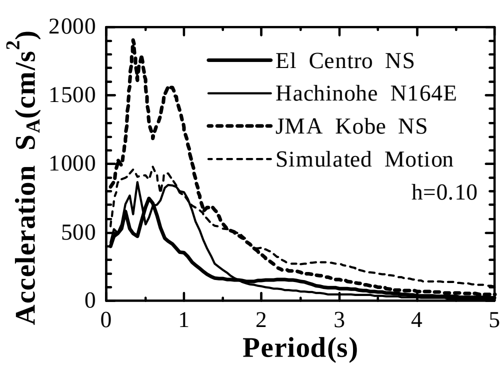


Figure 4. Acceleration Response Spectra

For input ground motions, records of El Centro NS (1940 Imperial Valley Earthquake), Hachinohe City Hall N164E (1994 Sanriku Haruka Oki Earthquake), Japan Meteorological Agency (JMA) at Kobe NS (1995 Hyogoken Nanbu Earthquake) and simulated ground motion are used. Acceleration time histories are shown in Figure 3, and acceleration response spectra are shown in Figure 4. Phase angles of simulated ground motions are given by uniform random values and Jennings type envelope function. Response spectrum is controlled to fit to the target response spectrum that has constant response acceleration range (from 0.16sec to 0.864sec), constant response velocity range (from 0.864sec to 3.0sec) and constant response displacement range (longer than 3.0sec).

RESPONSE VELOCITY AND RESPONSE PERIOD

Maximum Response

Momentary input energy ΔE in Figure 1 is given at each half cycle of response, and then the maximum ΔE in total duration time is $\Delta E_{\max}$. In this paper, maximum values are defined as follows.

- S_D ; Maximum response displacement in total duration time, or displacement response spectrum
- S_V ; Maximum response velocity in total duration time, or velocity response spectrum
- $\delta_{\max}$; Maximum response displacement in a half cycle of $\Delta E_{\max}$
- $V_{\max}$; Maximum response velocity in a half cycle of $\Delta E_{\max}$

By the results of response analysis of elastic SDOF systems with elastic period from 0.05sec to 5.0sec, comparison of S_D and $\delta_{\max}$, and comparison of S_V and $V_{\max}$ are shown in Figure 5. As for response displacement in Figure 5(a), because ΔE is considered to be related with the response displacement [1], S_D or almost same values of S_D occur just after $\Delta E_{\max}$ is inputted. On the other hand, as for response velocity in Figure 5(b), the difference between S_V and $V_{\max}$ is relatively large. Though there are many cases where $S_V = V_{\max}$, it is found that ΔE and response velocity is not always related and minimum values of $V_{\max}$ is about a half of S_V.

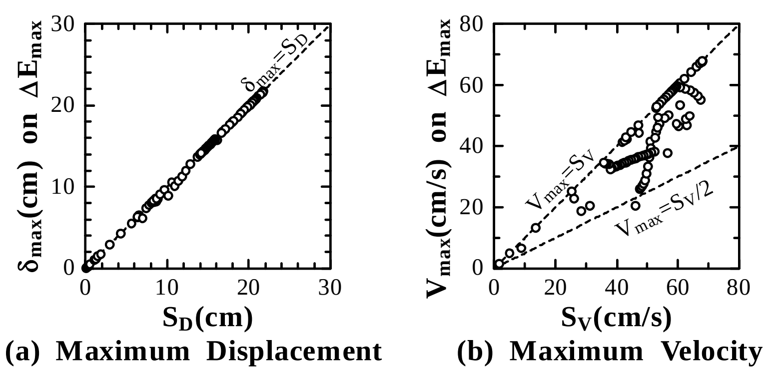


Figure 5. Comparison of Maximum Response (El Centro NS)

Response Velocity

In case of stationary response of elastic SDOF systems subjected to harmonic ground motions, maximum response velocity $V_{\max}$ is given by Equation (1) from maximum response displacement $\delta_{\max}$ and elastic period T. Generally $V_{\max}$ is estimated by this equation.

$$V_{\max} = \frac{2\pi}{T}\delta_{\max} \tag{1}$$

Ratio of response $V_{\max}$ to estimated $V_{\max}$ by Equation (1) is shown in Figure 6 by solid line. Ratio increases in long period range. Generally predominant period of earthquake is shorter than natural period or inelastic equivalent period of structures, and therefore actual response period of systems becomes shorter than T and actual response velocity becomes faster than that of Equation (1).

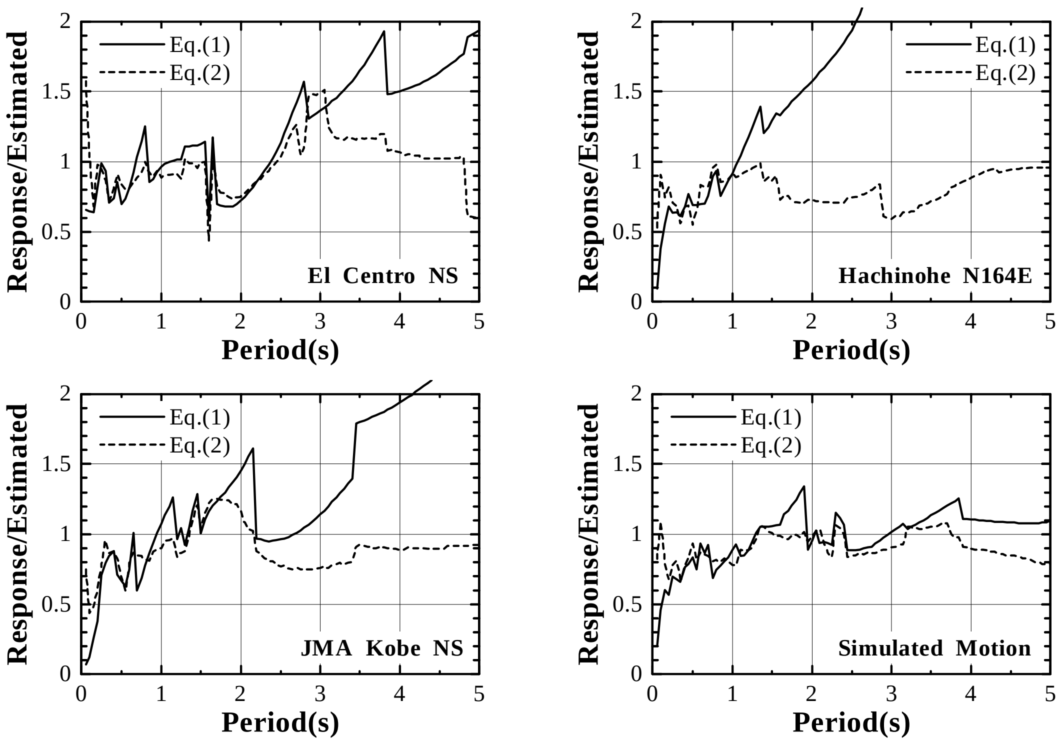


Figure 6. Ratio of Response Velocity to Estimated Velocity

To estimate appropriate $V_{\max}$, response period $2\Delta t$ is defined in this study. Δt is period of half cycle response in Figure 1 and Figure 2, then equivalent response period around $\delta_{\max}$ is assumed to be $2\Delta t$. Ratio of response $V_{\max}$ to estimated $V_{\max}$ by Equation (2) is shown in Figure 6 by broken line.

$$V_{\max} = \frac{2\pi}{2\Delta t}\delta_{\max} \tag{2}$$

Ratio is relatively stable around 1.0 in all period range. Appropriate $V_{\max}$ is found to be estimated by actual response period $2\Delta t$ instead of elastic period T .

Response Period

Response period $2\Delta t$ of elastic SDOF systems subjected to earthquakes are shown in Figure 7. $2\Delta t$ is equal to T in short period range, and is constant in long period range. The corner period is considered to be related to the peak period of response displacement spectra S_D shown in Figure 8. In long period range where S_D takes constant or decreasing values, $2\Delta t$ tends to be stable.

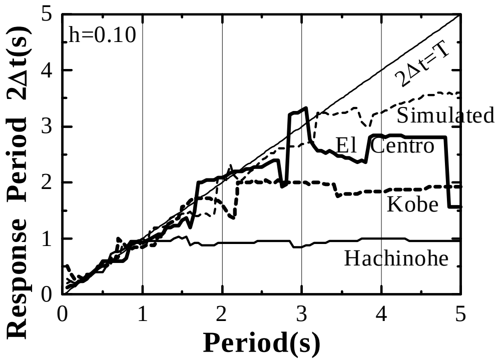


Figure 7. Response Period

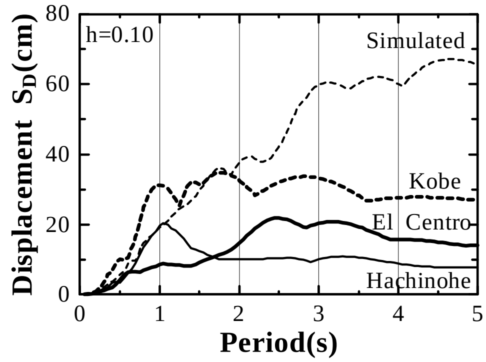
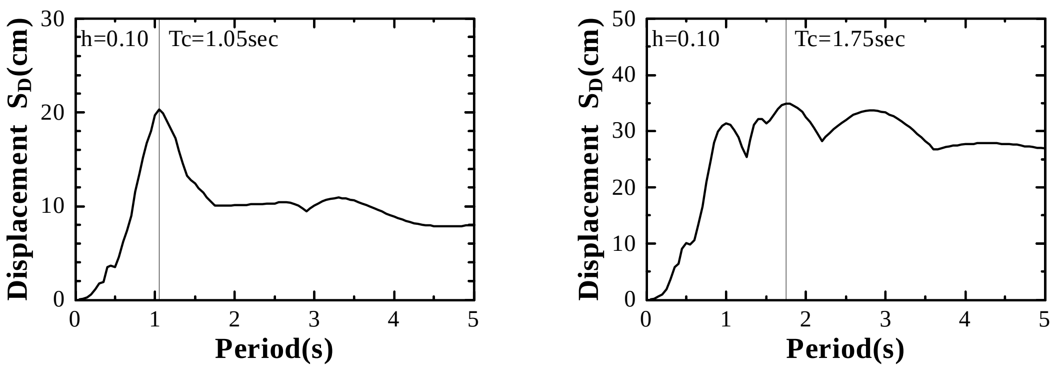


Figure 8. Displacement Response Spectra

ESTIMATION OF RESPONSE VELOCITY

Based on properties of response velocity and response period, an estimation procedure of response velocity is proposed. Estimation process and examples are introduced in the following.

1) Give response displacement spectrum S_D and define peak period T_C

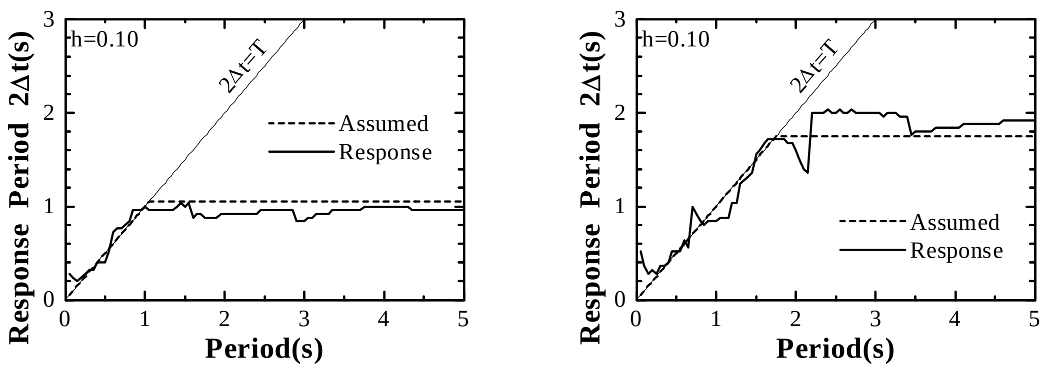


(a) Hachinohe N164E **(b) JMA Kobe NS**

Figure 9. Displacement Response Spectra

2) Regard T_C as corner period, assume response period $2\Delta t$ according to elastic period T

$$2\Delta t = \begin{cases} T & (T \le T_C) \\ T_C & (T > T_C) \end{cases} \tag{3}$$

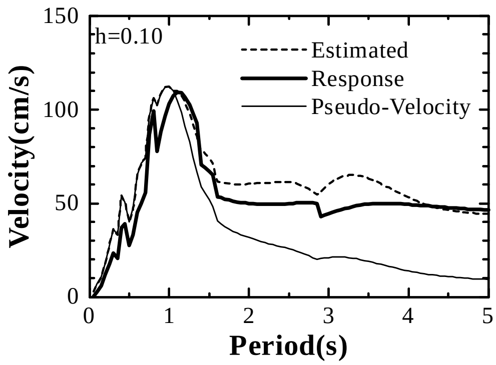


(a) Hachinohe N164E **(b) JMA Kobe NS**

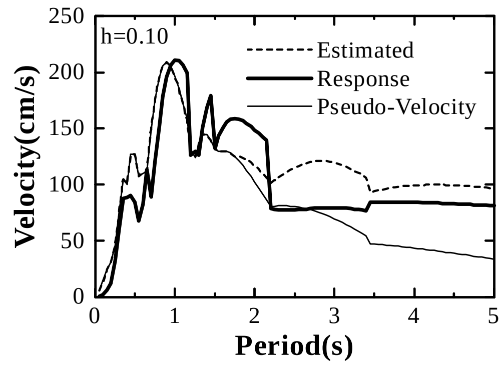
Figure 10. Response and Assumed Period

3) Estimate response velocity $V_{\max}$ by Equation (4)

$$V_{\max} = \frac{2\pi}{2\Delta t} S_D \tag{4}$$



(a) Hachinohe N164E



(b) JMA Kobe NS

Figure 11. Response and Estimated Velocity

Response and estimated $V_{\max}$ are shown in Figure 11, and almost appropriate values can be estimated. In the long period range, estimated values are overestimated. Because of shifted response of displacement, average displacement amplitude of a half cycle response is smaller than S_D though $2\Delta t$ does not change. In longer period range of T_C, pseudo-velocity ${}_pS_V$ given by Equation (5) decreases because of constant or decreasing values of S_D, but response $V_{\max}$ does not decrease. The difference between response $V_{\max}$ and ${}_pS_V$ is considered to influence to the difference between $2\Delta t$ and T.

$${}_pS_V = \frac{2\pi}{T} S_D \tag{5}$$

INELASTIC STRUCTURAL MODEL

For objective structure, 4 stories and 12 stories reinforced concrete frame structures are used in this study. By characteristics of these structures and eigenvalue analysis, properties of equivalent SDOF system are defined as shown in Table 1. Model L is equivalent to 4 stories frame structure and Model H is 12 stories.

Table 1. Analytical Model of SDOF System

	Model L	Model H
Initial Period	0.47sec	0.88sec
Yield Force F_y	6076kN	16444kN
Mass m	1332ton	4166ton
C_{By}	0.47	0.40

Yield Base Shear Coefficient $C_{By} = F_y / mg$ (g =9.8m/s^2)

As for inelastic force - displacement relationship of SDOF system, degrading trilinear type for reinforced concrete structures shown in Figure 12 is used. Viscous damping of structure is ignored for simplification of investigation. Damping factor of attached viscous damper is h =0.10 for each structural model.

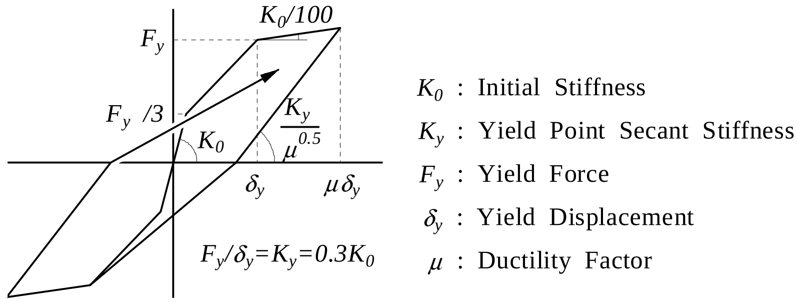


Figure 12. Model for Inelastic Force - Displacement Relationship

ESTIMATION OF DISSIPATED ENERGY BY STRUCTURES

The concept of energy based prediction is equalizing dissipated energy by structures to inputted energy by earthquakes. In this and following section, model and formulation of dissipated energy will be introduced, and prediction procedure will be shown.

In this section, model and formulation of increment of dissipated hysteretic energy ΔE_H by structure, and increment of dissipated damping energy ΔE_D by viscous damper during a half cycle response corresponding to maximum momentary input energy $\Delta E_{\max}$, are shown.

Dissipated Hysteretic Energy by Structure

Force - displacement relation of structures subjected to earthquakes are shown in Figure 13.

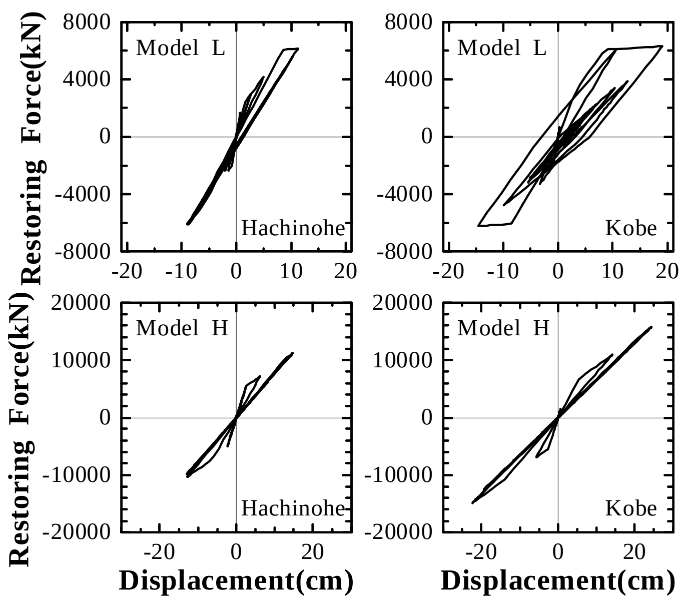


Figure 13. Force - Displacement Relation of Structures

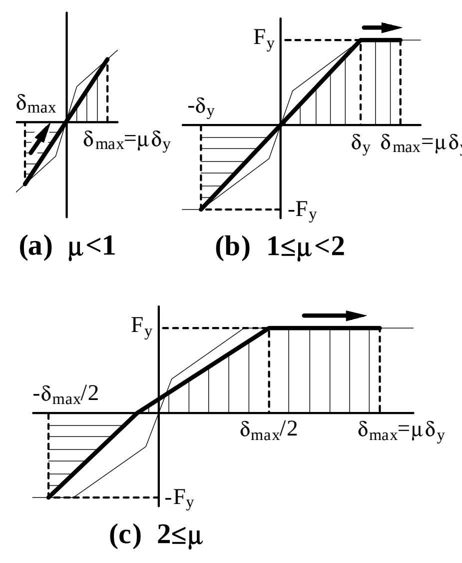


Figure 14. Model of Hysteretic Loop

By these results and so on, a half cycle response for this hysteretic model is assumed as shown in Figure 14 [1], and then increment of dissipated hysteretic energy ΔE_H is defined by vertical hatched area minus horizontal hatched area. ΔE_H is given by Equation (6). According to this formulation, ΔE_H is represented by response ductility factor μ.

$$\Delta E_H = \begin{cases} 0 & (\mu < 1) \\ (\mu - 1) F_y \delta_y & (1 \le \mu < 2) \\ \left(\mu - \sqrt{\dfrac{\mu}{2}}\right) F_y \delta_y & (2 \le \mu) \end{cases} \tag{6}$$

Dissipated Damping Energy by Viscous Damper

Figure 15 shows response damping force during a half cycle response corresponding to $\Delta E_{\max}$. Solid line is the response damping force, and broken line is the assumed ellipse which will be mentioned later in this subsection. In case of stationary response of elastic SDOF systems subjected to harmonic ground motions, damping force - displacement relation of viscous damper makes ellipse loop. In this section, formulation of increment of damping energy ΔE_D is shown according to a number of assumptions.

1) Assumption of Ellipse

By assuming damping force - displacement relationship as ellipse as shown in Figure 16, ΔE_D is given by Equation (7).

$$\Delta E_D = \frac{1}{2} \pi c V_{\max} a \tag{7}$$

where a is the average displacement amplitude.

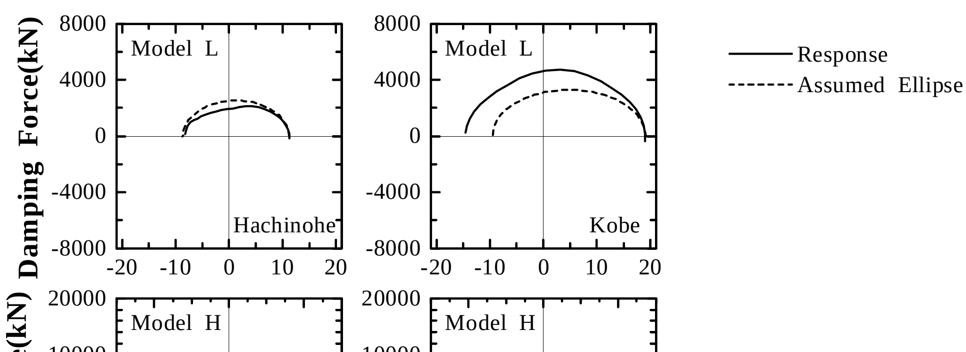


Figure 15. Force - Displacement Relation of Damper

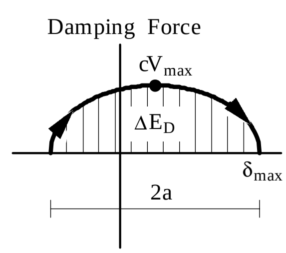


Figure 16. Model of Damping Force

2) Average Displacement Amplitude
Average displacement amplitude a is formulated by model of hysteretic loop in Figure 14.

$$a = \begin{cases} \mu\delta_y & (\mu < 1) \\ \dfrac{\mu\delta_y + \delta_y}{2} = \dfrac{\mu+1}{2}\delta_y & (1 \le \mu < 2) \\ \dfrac{\mu\delta_y + \mu\delta_y/2}{2} = \dfrac{3}{4}\mu\delta_y & (2 \le \mu) \end{cases} \tag{8}$$

3) Equivalent Period and Response Period
Equivalent period T is defined by secant stiffness of maximum response of structures. And response period $2\Delta t$ is given by Equation (3) with considering influence of input ground motions.

4) Maximum Response Velocity
Response velocity $V_{\max}$ is estimated by Equation (2).

Broken line in Figure 15 is assumed ellipse by response $\delta_{\max}$, assumed a and $V_{\max}$. In case of Hachinohe, assumed ellipse can simulate response results well, but in case of JMA Kobe, difference of displacement amplitude is shown.

Comparison of Dissipated Energy
Figure 17 shows comparison of dissipated energy. In case of Model L estimated energy can estimate the response energy approximately. However because of unsuitable assumption for ΔE_H in smaller ductility factor range, ΔE_H of Model H is zero. But ΔE_D of both Models are estimated well, and because of relatively larger values than ΔE_H, inaccuracy of estimated ΔE_H is improved on total dissipated energy $\Delta E_H + \Delta E_D$.

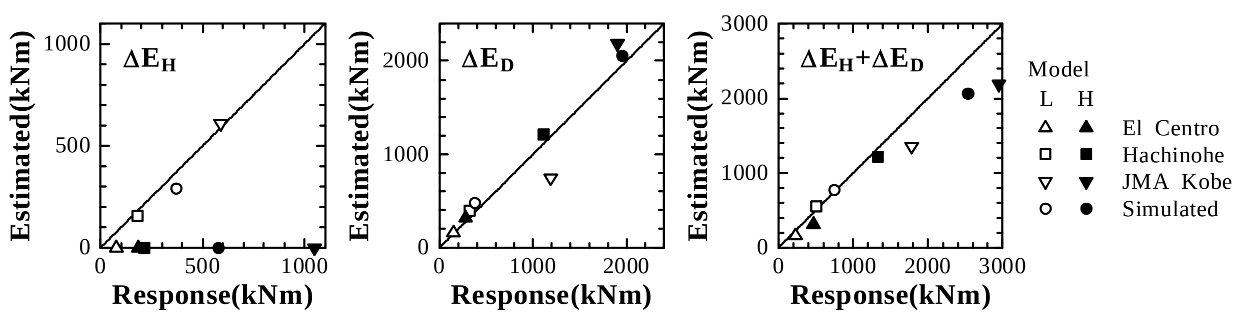


Figure 17. Comparison of Dissipated Energy

PREDICTION OF MAXIMUM RESPONSE

A response prediction procedure of maximum response displacement is shown with examples.

(1) Define Structure and Input Ground Motion
As examples, response prediction of Model L and Model H subjected to Hachinohe N164E and JMA Kobe are explained.

(2) Input Energy of Ground Motion

Energy equivalent velocity $V_{\Delta E}$ is determined as follows.

$$V_{\Delta E} = \sqrt{\frac{2\Delta E_{\max}}{m}} \tag{9}$$

$V_{\Delta E}$ can be estimated approximately by Equation (10) [2].

$$V_{\Delta E}(T,h) = \sqrt{2\pi h(1.2+0.2T)}\,{}_pS_V(T,h) \tag{10}$$

Response $V_{\Delta E}$ and estimated $V_{\Delta E}$ by Equation (10) are shown by solid line in Figure 18. Estimated $V_{\Delta E}$ will be used in the following prediction process.

(3) Equivalent Period

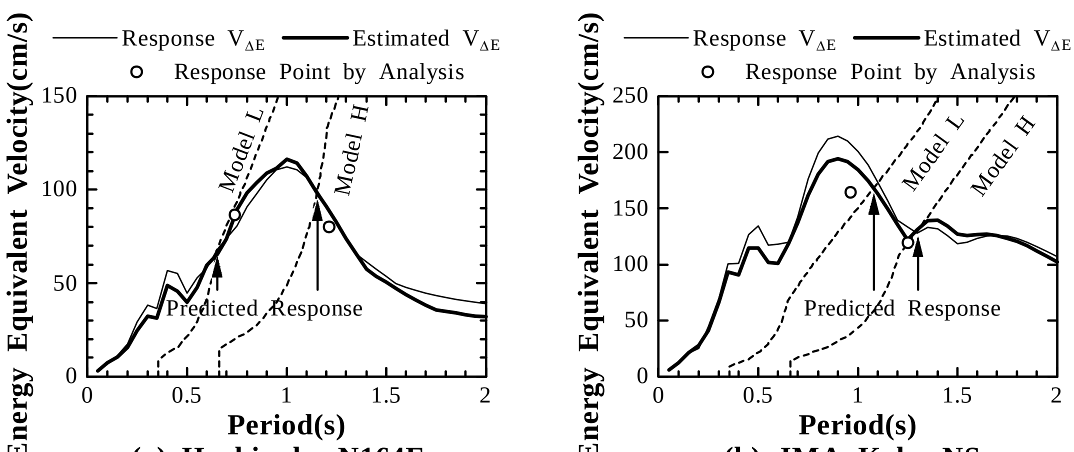
Equivalent period of structures is assumed to be 0.75 times of period given by secant stiffness of maximum response. 0.75 is coefficient to consider the influence of shorter predominant period of input ground motions. Equivalent period is formulated as function of response ductility factor μ.

(4) Dissipated Energy by Structure and Viscous Damper

ΔE_H is given by Equation (6) as a function of μ. ΔE_D is given by Equation (7) and so on as a function of μ. And then, $\Delta E_H + \Delta E_D$ is given as function of μ. Broken line in Figure 18 is the relationship between $\Delta E_H + \Delta E_D$ and equivalent period by parametric μ. This broken line indicates the energy dissipating capacity and equivalent period of each structural model on a certain response displacement.

(5) Response Prediction

In Figure 18, the cross point (pointed by arrows) of input energy (thick solid line) and dissipated energy (broken line) indicate the energy equivalent period, that is, the equivalent period of predicted displacement. By the comparison with plotted point of response analysis results, it is considered that predicted displacement can estimate approximately.



(a) Hachinohe N164E (b) JMA Kobe NS

Figure 18. Prediction of Maximum Response

CONCLUSIONS

In this study, energy dissipating behaviors and response prediction of reinforced concrete structures with viscous dampers are investigated for the purpose of applying to performance based earthquake resistant design. Then the following conclusions are found.

1) For the seismic resistance of viscous dampers, evaluation of response velocity is important. It is found that response velocity is estimated by response period that depends on spectral properties of ground motions. Response period is equal to elastic period of structures in short period range, and is constant in long period range. As for viscoelastic dampers that have velocity depending stiffness and damping characteristics, the influence of response period is considered to be important particularly.

2) Seismic resisting capacity of viscous damper should be evaluated not only by the damping force but also by the dissipated damping energy. By a number of assumptions including response velocity and response period, increment of dissipated damping energy is formulated and estimated well.

3) A procedure to predict inelastic response displacement by equalizing dissipated energy to earthquake input energy is proposed. Because energy dissipating behaviors are evaluated by considering hysteretic and damping properties of structures, this procedure can be applied to various structures with respective appropriate assumptions.

REFERENCES

1. Hori N., Inoue N., “Damaging Properties of Ground Motions and Prediction of Maximum Response of Structures based on Momentary Energy Response”, Earthquake Engineering & Structural Dynamics, Vol.31, No.9, pp.1657-1679, 2002.
2. Hori N., Iwasaki T., Inoue N., “Damaging Properties of Ground Motions and Response Behavior of Structures based on Momentary Energy Response”, 12th World Conference on Earthquake Engineering, No.839, Auckland, New Zealand, 2000.